Acta Materialia 104 (2016) 295–302

Contents lists available at ScienceDirect

Acta Materialia

journal homepage: www.elsevier.com/locate/actamat

Full length article

Persistent slip bands: Similitude and its consequences

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A R T I C L E I N F O

Article history:
Received 21 July 2015
Received in revised form
29 October 2015
Accepted 4 November 2015

Keywords:
Persistent slip bands
Similitude
Saturation stress
Modeling
Screw dislocations

A B S T R A C T

The similitude properties of persistent slip bands (PSBs) in cycled copper and nickel crystals are determined with optimal accuracy from three published sets of experimental data covering a wide temperature range. These properties are analyzed in terms of Brown's bowing and passing model for screw dislocations, which predicts that PSB channels should follow similitude. Several unexpected original features are obtained. The PSBs and the PSB channels follow similitude relations. The maximum temperatures for the occurrence of a saturation plateau appear to be related to the emergence of secondary dislocations in the microstructure. The flow stresses of the channels were found comparable to predicted values. They are, however, somewhat smaller than the saturation stresses. Thus, the bowing and passing model can accommodate a small resistance opposed by internal stresses and/or various defects to the motion of screw dislocations in PSB channels. Finally, it seems confirmed that the measured temperature and material dependencies of PSB channel properties arise from the thermally activated annihilations of screw dislocations.

1. Introduction

Among the various microstructures formed during the cyclic deformation of ductile materials, persistent slip bands (PSBs) in f.c.c. metals have been the subject of many experimental and theoretical studies, as well as several review articles and chapters (see e.g. Refs. [1–5]). PSBs are thin bands of localized plastic strain formed during cyclic deformation at medium plastic strain amplitudes per cycle, typically from 10^{-4} to 10^{-2}. They are observed in single slip and are parallel to the primary slip plane. These slip bands extend all through a single crystal or a grain in a polycrystal; they promote the occurrence of fatigue damage at free surfaces or in the bulk [6]. During cycling, the maximum stress of the hysteresis loops increases and eventually saturates when PSBs are formed. From this point on, PSBs accommodate the imposed plastic strain amplitude under a constant saturation stress. Thus, within a certain range of plastic amplitudes, a well-defined saturation plateau is observed in the cyclic stress vs. strain curves.

PSBs exhibit a rather regular wall and channel microstructure. A section perpendicular to the band and parallel to the primary Burgers vector reveals a rather regular ladder structure, in which the rungs contain a high steady state density of small, elongated edge loops lying in the cross-slip plane of the primary screws, plus jogged edge lines. Between these walls, the less dense channels mainly contain a steady state density of screw dislocations that move back and forth and are thought to carry most of the plastic strain amplitude.

The modeling of the saturation stress is the subject of long-standing discussions [4], which are mainly focused on two different types of approaches. In the composite model proposed by Mughrabi and co-workers, PSBs are treated as a composite material made up of a hard wall phase and a soft channel phase (see Ref. [7] for a full review). The condition for compatible deformation entails the occurrence of internal stresses. In the soft channels, the internal stresses are resistive and their average value amounts to a substantial fraction of the saturation stress. Conversely, in the thin hard walls, these stresses are positive and their average magnitude is much larger. In this model, the mutual annihilation of screw dislocations in PSB channels is considered as a purely mechanical, stress-assisted process. Hence, the athermal stress acting on screw dislocations was originally taken as the sum of their Orowan bowing stress, of a small thermally activated stress arising from the local interactions of screw dislocations with other defects and of the internal stresses mentioned above.

Brown's bowing and passing model for dislocations in PSB

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http://dx.doi.org/10.1016/j.actamat.2015.11.010
1359-6454/

channels [8] was elaborated in two successive steps [9,10]. As discussed in Refs. [8,10], the average internal stresses in the channels should not contribute substantially to their flow stress. It is also assumed that the thermally activated annihilation of screw dipoles by cross-slip governs the critical stress in the channels. The flow stress of the channels, which is implicitly assimilated to the saturation stress, is the sum of the Orowan stress of screw dislocations and of an additional contribution from the dipole passing stress (cf. Fig. 1). No additional stress is explicitly incorporated in the model to account for possible interactions of screw dislocations with various types of defects.

Upon discussing an early version of the bowing and passing model [10], Mughrabi and Pschenitzka [11] performed calculations showing that the flow stress of the channels should be equal to whichever of the bowing or passing stress is the larger. The flow stress would then be at most about 20% larger than the larger of the two stresses. In the final version of the bowing and passing model [8], the flow stress is about 50% of the Orowan stress. In addition, there is still no agreement between the two models about whether long-range internal stresses are significant or not and about whether or not screw dislocation annihilations are thermally activated or not. These questions are reflected, in recent dislocation dynamics simulations (see Refs. [12,13] for references).

The present study is based on the similitude relation, which was introduced by D. Kuhlmann–Wilsdorf as a consequence of her 'mesh-length' theory and developed under the name of 'similitude principle' [14]. This relation applies to materials where the critical bowing of mobile dislocations interacting with a dislocation forest governs the flow stress. Then, the critical stress is inversely proportional to the average distance between strong forest obstacles along the lines. It follows that the characteristic wavelength of the microstructure is always proportional to this average distance and, hence, inversely proportional to the flow stress. This property was extensively verified by investigations performed at fixed and variable temperatures, in f.c.c. crystals and other materials, in unidirectional deformation [15] and in cyclic deformation (see e.g. Ref. [1], for cell structures and [3] for PSB channels). The available experimental results were compiled in a recent review article [5].

According to the bowing and passing model, the flow stress of the channels follows a similitude relation involving the channel width. If it is so, the characteristic width of PSBs, which is the sum of a channel width and of a wall thickness, may not follow such a relation because the wall thickness is a constant (Section 2). The composite model does not consider the similitude property; in addition, some doubts were expressed about its validity [7]. Therefore, the objective of the present work is to investigate from experimental results the similitude properties of PSBs and PSB channels.

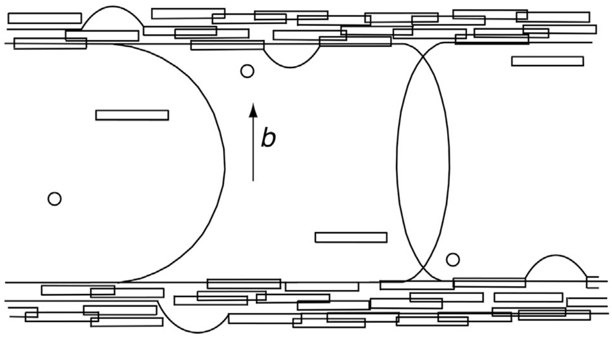

Fig. 1. Schematic view of a PSB parallel to the slip plane of the screw dislocations (Burgers vector *b*). The walls contain a high density of small, elongated prismatic loops and edge lines. In the channels, the screw dislocations bow out critically (left) and experience dipolar interactions (right). They also interact with various types of dislocation debris represented by small prismatic loops and vacancy clusters.

Three sets of data measured on PSBs as a function of temperature are selected, two on copper [4,16,17] and one on nickel [18,19]. A first unexpected result emerges at once, as the similitude relation is perfectly verified in PSBs (Section 2). Assimilating the critical stress of the channels to the saturation stress reveals two new features (Section 3). The first one is interpreted as reflecting the transition from PSBs to cell structures. The other one is concerned with a comparison of the experimental critical stresses with the ones predicted by the bowing and passing model. Some results are further discussed in Section 4 and the major conclusions of the present study are given in Section 5.

2. Methodology

This section discusses first the selected experimental data on the evolution of PSB properties as a function of temperature in single crystals of copper and nickel oriented for single slip. Tests of the similitude relation on PSBs are presented next in order to illustrate how the related coefficient can be drawn from experiment with optimal accuracy.

2.1. Experimental data on PSBs

For copper, the measurements reported by Basinski and Basinski [4] were carried out at 4.2, 77 and 295 K. A second study on copper was performed by Holzwarth and Essmann [16,17] between 77 and 430 K. The data are taken from the latest publication [17] and are complemented by the scatter of the mean channel widths given in Ref. [16]. In what follows, these two data sets are referred to as $\mathrm{Cu_{BB}}$ and $\mathrm{Cu_{HE}}$. It will be shown that they can be lumped together in order to obtain a single data set with improved accuracy between 4.2 and 430 K.

The channel widths distributions were investigated in copper by Holtzwarth and Essmann [16,17]. These widths exhibit a wide spreading, for example from 0.7 μm to 2.3 μm at 300 K, irrespective of the previous cycling history. For a saturation stress $\tau_{\mathrm{PSB}} = 28$ MPa at 300 K, the arithmetic mean channel width d_{ch} is, however, rather well defined ($d_{ch} = 1.44 \pm 0.04$ μm). This value is somewhat larger than the commonly quoted one of about 1.2 μm. The mean wall thickness d_w does not depend on temperature [17]; its value is $d_w = 0.11 \pm 0.01$ μm. As Basinski and Basinski [4] did not measure wall thicknesses, advantage was taken from this property to determine the mean PSB widths $d = d_{ch} + d_w$ from the measured mean channel widths.

In nickel, the experimental results comprise four data points between 77 and 750 K [18,19]. Some additional information can be found in an article by Bretschneider et al. [20], in particular regarding uncertainties about the data point at 750 K. Three different values are given for its saturation stress, of which one [19] was taken in a 'plateau-like' stage associated with some cyclic hardening. The two other values [18,20] are virtual ones; they were obtained by back-extrapolating the saturation stress to the beginning of the plateau-like stage. The wall thicknesses fluctuate by ±10% as a function of temperature around an average value of $d_w = 0.155$ μm without showing any definite trend (Tippelt et al. [19]). The data for nickel are taken from the latest publication, by Hähner et al. [18], except for the wall thicknesses that were rounded off; their measured and mean values are taken from Ref. [19].

Below 100 K, nickel and copper samples cycled at saturation exhibit an extended, irregular wall structure [21]. This led to some discussions about whether or not these microstructures can be considered as PSBs [4,16,20,21]. As was done in Refs. [4,17,18], it is